

## RELATED APPLICATIONS

This application is a divisional of application Ser. No. 09/599,409 filed June 22, 2000, entitled "A Process to Fracture Connecting Rods and the Like with Resonance-Fatigue", which is incorporated herein by reference.

## 5 BACKGROUND OF THE INVENTION:

### (I) Prior Art Background

Many methods have been used in fracturing connecting rods, that include:

- (i) Passing an electron beam along a desired splitting plane as in U.S. Patent No 3,751,080.
- 10 (ii) Providing holes in the fracturing plane through which the fracturing force is introduced as in U.S. Patent No. 3,994,054
- (iii) Using heat treatment or freezing to embrittle the fracture area as in U.S. Patent No. 4,768,694
- (iv) Applying a static or an impulsive force acting perpendicular to the fracture plane as  
15 in U.S. Patent Nos. 4,860,419; 5,115,564; and 5,320,265.
- (v) Actuating expanding mandrels using a wedge arrangement as in U.S. Patent No 5,503,317.

However, most of the known methods for fracturing the connecting rods are based on the same principle: application of an "outward pressure" to the crank bore till  
20 the generated stresses are high enough to fracture the connecting rod. Some of these methods attempted to overcome the difficulty of fracturing such high strength material by reducing or weakening the cracking area, by using techniques, such as, the cryogenic cooling and the electron beam hardening, which have a deleterious effect on material performance.

25 Since connecting rods are made of high strength materials, the fracturing force is required to be of big magnitude. The use of big force has a negative effect on the quality of the fractured connecting rod, especially, with large size connecting rods in a high production environment. Despite the improvements, some disadvantages still exist such as: plastic deformation, lack of flexibility in adapting the same technique to different  
30 sizes of connecting rods, repeated breakage of force exertion elements of the machine,

and poor quality of the fractured connecting rod. Moreover, some techniques are slow, costly, and technically very elaborate.

Before presenting the idea of the current invention, it is necessary to discuss the engineering principles on which the invention stands.

## 5 (II) Technical Background

### (A) Fracture Mechanics:

Strength failures of load bearing elements can be either of the yielding-dominant (ductile) or fracture-dominant (brittle) types. In case of a cracked element, it may fail due to reaching the plastic collapse or fracture condition. Collapse and fracture are  
10 competing conditions, and the one satisfied first will prevail.

High-strength materials are more likely to fail in fracture mode before attaining the plastic collapse strength. Since connecting rods are made of high-strength materials, they generally fail under tensile forces due to reaching the fracture limit state.

Fracture may take place under one of two conditions, namely, plane stress or  
15 plane strain, depending on the thickness of the element. In general, connecting rods are thick enough to sustain plane strain fracture. In the presence of a V-notch or a crack, fracture occurs under essentially elastic conditions with a limited plasticity zone at the tip of the crack.

The stress intensity factor ( $K$ ), is the characterizing parameter for crack  
20 extension. For each stress pattern, there is a corresponding value of the stress intensity factor. When the stress intensity factor reaches a certain value, crack propagates and collapse by fracture occurs. That critical value of the stress intensity factor under plane strain conditions, called the Plane Strain Fracture Toughness ( $K_{Ic}$ ), can be considered as a material property characterizing the crack resistance. Thus, the same value of  $K_{Ic}$   
25 should be obtained for a given material while testing specimens of different geometric shapes and sizes.

Lower temperature and faster strain rate decrease the plane strain fracture toughness for a specific material, while increasing the length of a pre-existing crack or decreasing the fracturing area will increase the stress intensity factor, if all other factors  
30 remain unchanged.

### (B) Resonance of a Structural System:

The connecting rod, with all movement and rotation constraints imposed on it during the fracturing process, can be viewed as a structural system. Before explaining how to achieve and make use of a resonance condition in this fracturing technique, it is helpful to introduce the following definitions pertaining to an idealized structural system with finite number of degrees of freedom:

Degrees of freedom: the number of independent displacements required to define the displaced positions of all the masses relative to their original positions is called the number of degrees of freedom (DOFs).

Natural mode of vibration: a multi-degree-of freedom system (MDOF) would undergo simple harmonic motion, without a change of the deflected shape, if free vibration is initiated by appropriate distribution of displacements in various DOFs. In other words, for some characteristic deflected shapes, the system would vibrate in simple harmonic motion, and the initial shape would be maintained through out the motion. Each characteristic deflected shape ( $\Phi_n$ ) is called a natural mode of vibration of the MDOF system.

Natural vibration properties: the time ( $T_n$ ) required for a system to complete one cycle of the simple harmonic motion in one of its natural modes is called the natural period of that particular vibration mode. The corresponding natural cyclic frequency of vibration is  $f_n$ , and the natural circular frequency of vibration is  $\omega_n$ , where:

$$T_n = 2\pi/\omega_n = 1/f_n.$$

A vibrating system with N number of DOFs has N natural vibration frequencies  $\omega_n$  ( $n = 1, 2, \dots, N$ ), arranged in sequence from smallest to largest ( $\omega_1 < \omega_2 < \dots < \omega_N$ ), with corresponding natural periods  $T_n$ , and natural modes  $\Phi_n$ .

The excitation frequency: the frequency of a harmonic force applied to a system is called the excitation frequency or the forcing frequency.

Damping: the process by which vibration steadily diminishes in amplitude is called damping.

## SUMMARY OF THE INVENTION

The present invention employs a novel approach to fracture connecting rods. In this process, several factors are used to raise the stress intensity factor in the connecting rod up to the fracture point. Consequently, the use of single big force has been avoided

with the application of several small magnitude forces. That eliminates many problems associated with the use of big forces. It also gives better control over the fracturing process, since the contribution of each factor is optimized to achieve the best results.

For this process, a stress-riser should be provided in a prior process, using any of the  
5 known methods, in order to predetermine the fracture plane.

The present invention utilizes the following factors:

(a) Fatigue: if the stresses in a pre-notched connecting rod fluctuate due to the application of harmonic forces (or any time varying forces), the pre-existing crack (stress-riser) will extend incrementally depending on the range of fluctuation in the  
10 stress intensity factor. It is important to notice that the crack growth relates to the change of the stress intensity factor, not to its absolute value. Moreover, as the crack grows, the absolute value of stress intensity factor will increase.

(b) Resonance: during the fracturing process, the connecting rod will be in contact with many elements of the machine. These elements impose movement  
15 constraints, called geometrical boundary conditions, to the connecting rod. The connecting rod, with these boundary conditions, represents a distributed mass structural system, with an infinite number of degrees of freedom. However, it can be idealized and analyzed as a system with finite number of degrees of freedoms by using the finite element method.

If a MDOF structural system is subjected to an external force system, where the  
20 spatial distribution of the force components is independent of time, it takes a certain deformed shape. This shape does not necessarily resemble any of the natural vibration modes of the system. However, it has the same configuration as one of these natural modes, and with judicious selection of the external forces, the forced deformed shape  
25 can present a better approximation to that mode  $\Phi_r$ , which has a natural frequency  $\omega_r$ . In most cases,  $\Phi_r$  is one of the first few natural modes.

If the force components have the same sinusoidal time variation, with a frequency that is the same as or close to the natural frequency  $\omega_r$ , a resonance condition occurs. Consequently, the fluctuation range of the stress intensity factor and its  
30 maximum value increase substantially. The crack extends, and fracture may occur,

depending on the relative magnitudes of stress intensity factor and material fracture toughness.

The aforementioned principle is applied in the present invention, where two harmonic forces, with the same amplitude and a phase angle of  $180^\circ$ , are applied simultaneously to two sides of the connecting rod. The two forces act along a straight line parallel to the predetermined fracture plane and perpendicular to the axis of the bore cylindrical surface. Moreover, the clamping arrangement allows free deformation of major part, centered on the V-notch, of each of the two webs defining the bore.

A suggested method, to apply the two harmonic forces, is to transform the rotary motion generated by a hydraulic motor to a couple of rotary motions, one clockwise and another anti-clockwise. These rotary motions can be transformed to linear motions using cam means, which transfer the pressure to the connecting rod through two contacts. The use of a single motor will guarantee that there is no time lag between the two equal but opposite forces.

(c) Pre-stressing forces: three pre-stressing forces are applied in the present invention. The primary one is applied by moving an upper jaw, which is part of the clamping arrangement, in a direction perpendicular to the predetermined fracture plane and away from it. This force works to eliminate the compression stress zones created by the harmonic forces and to decrease the deformation due to its application, giving more rigidity to the system. Eliminating the compression zones is favorable, since they deviate the fracture from predetermined plane.

The secondary pre-stressing forces are two static forces, equal in magnitude and acting on the same straight line in opposite directions, toward the bore axis. The same mechanism used to apply the harmonic forces can be used to apply these forces. Firstly, the two contacts advance till they slightly press the part applying the secondary pre-stressing forces, and secondly, they move forward and backward applying the harmonic forces.

These forces have clamping and damping actions. However, since they act in the same opening loading mode as the primary force, the stresses due to all of them can be superimposed. This will facilitate further reduction of the high magnitude fracturing forces.

Under the effect of the external forces, the deformed shape of the connecting rod changes with time. However, during each cycle, it passes through maximum and minimum deformation positions at time instants  $T_{\max}$  and  $T_0$ , respectively. The stress intensity factor corresponding to the harmonic forces has a maximum value at the maximum deformation position. Both of  $T_0$  and  $T_{\max}$  can be determined analytically by knowing the characteristics of the forces.

(d) Dynamic force: a dynamic force is finally applied at a time instant  $T_f$ , by increasing the primary pre-stressing force suddenly as an impulsive force at  $T_f$ , or at a slower rate within a period centered on  $T_f$ . The time instant  $T_f$  to be determined by performing several simple tests, by applying the fracturing force during different cycles at different time instants such as  $T_0$  (minimum deformation) or  $T_{\max}$  (maximum  $K_I$ ) and comparing the quality of the fractured connecting rods.

For example, if  $T_0$  comes after 0.10 seconds from the beginning of each cycle, and the natural vibration period is 0.25 second, a test can be performed by applying an impulsive force at  $T_0$  during the cycle 101 after 25.10 seconds from the beginning of the harmonic excitation. In another test, a dynamic force is applied during a period starting from the instant 25.05 seconds, and ending at the instant 25.15 seconds, measured from the beginning of the excitation. Similar tests are performed by applying the fracturing force during different cycles, and at different time instants, and by comparing the quality of the fractured connecting rods,  $T_f$  is identified. However, a longer period before applying the dynamic force, increases the fatigue effect.

All of the external forces used in the aforementioned factors are in the same loading mode and, generally, stress the connecting rod within the linear elastic regime. Thus, the stress intensity factor due to their collective effect,  $\Sigma K_I$ , is obtained by adding the values of  $K_I$  that correspond to each one of them, if applied individually. Fracture occurs when  $\Sigma K_I = K_{Ic}$ .

The flexibility of the external force system used in the current invention, makes the technique suitable for the wide variety of connecting rods types and sizes, starting from those intended for light duty applications such as lawnmowers and outboard marine engines, up to the most powerful combustion engines.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows the integrally formed connecting rod, where 1A is the part intended to become the rod, 1B is the part intended to become the cap. 1C<sub>L</sub> and 1C<sub>R</sub> are the stress-riser, 1D<sub>L</sub> and 1D<sub>R</sub> are the sides where the harmonic forces and the secondary pre-stressing forces are applied, and 1E is the predetermined fracture plane.

Figure 2 shows an idealization of a connecting rod as a structural system.

Figure 3 shows the external force system used to fracture the connecting rod, where  $F_1$  is the primary pre-stressing force;  $F_{2L}$ ,  $F_{2R}$  are the secondary pre-stressing forces;  $F_{3L}$ ,  $F_{3R}$  are the harmonic forces; and  $F_{4I}$ ,  $F_{4D}$  are the impulsive and the slow rate dynamic force, respectively. It also shows the clamping arrangements and the force exerting elements of the machine; where 2 is the upper jaw; 3 is the lower jaw; 4<sub>L</sub>, 4<sub>R</sub> are the two contacts; and 6; 7; 8; 9; 10; 11 are other clamping elements.

Figure 4 is a cross sectional view taken along line 5 of Figure 3.

Figure 5 shows the deformed shape of the connecting rod under the effect of the pre-stressing forces and the harmonic forces. The deformed configuration is exaggerated for clarity.

Figure 6 shows the first three natural vibration modes of the idealized structural system. Notice how the first mode (Mode 1) has the same configuration of the deformed shape of the structure shown in Figure 5.

Figure 7 shows the different modes of loading a cracked structural element, all forces used in this structural system are in the opening mode.

## DESCRIPTION OF THE INVENTION:

The following is a description of the two parts of the process, the stress analysis, and the process implementation:

### (I) Stress Analysis

A stress analysis should be performed once for each type of connecting rods, using any appropriate computer software package according to the following steps:

- (a) Creating a three dimensional solid model of the connecting rod.
- (b) Idealizing the connecting rod as a structural system, using the solid model with the movements and rotation constraints that represents the geometrical boundary

conditions, and determining the first few natural vibration frequencies and mode shapes of the system, using the finite element method.

(c) Determining the characterizing deformed shape of the system under the effect of a couple of harmonic forces with amplitude equal to unity, a primary pre-stressing force, and a couple of secondary pre-stressing forces, each with magnitude of unity, applying all simultaneously.

(d) Defining the natural mode shape  $\Phi_r$  that has the same configuration as the deformed shape determined in step (c), and its corresponding natural frequency  $\omega_r$ .

(e) Determining the deformed shapes of the system under the effect of the forces described in step (c) applying each individually.

(f) Using the results of step (e), an optimum combination of the harmonic and pre-stressing forces is determined that produces a deformed shape closely resembling the modal shape  $\Phi_r$ .

(g) Determining the time instants  $T_0$  and  $T_{\max}$ , measured from the beginning of any harmonic cycle, where  $T_0$  is the time instant at which the deformed shape of the connecting rod is the closest to its original shape,  $T_{\max}$  is the time instant at which the stress intensity factor, corresponding to the harmonic forces, has a maximum value.

## (II) Process Implementation:

Firstly, the connecting rod is clamped in position on the upper jaw 2, which is movable in direction perpendicular to the predetermined fracture plane, and on the lower jaw 3, which is stationary. Both jaws are in contact with the inside cylindrical surface of the bore, while other elements 6, 7, 8, and 9 are pressing the connecting rod surface against the two jaws. It is supported at points 10 and 11 as shown in figure 3. However, the exact locations of these points depend on connecting rod configuration and manufacturing requirements.

Secondly, the pre-stressing force  $F_1$  is applied, by moving the upper jaw away from plane 1E.

Thirdly, the two contacts 4 and 5 advances, in opposite directions, to contact the sides  $1D_L$  and  $1D_R$  applying the secondary pre-stressing forces  $F_{2L}$  and  $F_{2R}$ .

Fourthly, the two contacts  $4_L$  and  $4_R$  move forward and backward, simultaneously, applying the two harmonic forces  $F_{3L}$  and  $F_{3R}$ , with a phase angle of  $180^\circ$ , while their



frequency is as close as practically possible to the selected natural frequency of the system.

Fifthly, an impulsive fracturing force  $F_{41}$  is applied at the time instant  $T_f$ , causing a sudden increase of  $F_1$  and, thus, fracturing the connecting rod.  $T_f$  is determined first, by  
5 performing the tests that were described earlier.

An alternative to execute the last step is to apply a slow rate dynamic force within a period centered on the same time instant.

Although the preferred mode for carrying out this invention has been set forth in this specification, it is obvious that there are several alternative modes. One of them for  
10 instance, is to apply a harmonic force to the cap, in a direction that is perpendicular to the predetermined fracture plane.

While the present description of the process incorporates all of the aforementioned factors, eliminating the pre-stressing forces or either of them should not be construed as a departure from the scope of this invention. This is a valid option,  
15 especially, for small size connecting rods. In this case, the procedure that was described earlier should be followed, with an exception that is to skip the steps related to the omitted force or forces.

While particular embodiments of the invention have been disclosed, it is evident that many alternatives and modifications will be apparent to those skilled in the art in  
20 light of the forgoing description. Accordingly, it is intended to cover all such alternatives and modifications as fall within the spirit and broad scope of the appended claims.